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Contemporary approaches to reducing weld-induced residual stress

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Abstract

Self-equilibrating residual stresses may occur in materials in the absence of external loading due to internal strain inhomogeneity. While favourable distributions of residual stress can bestow an object with the appearance of superior material properties, most welding processes leave behind residual stresses in particularly unfavourable patterns, causing a greater susceptibility to fracture-based failure mechanisms and unintended deformation. Currently, heat treatment is the primary means of removing these stresses, but since the formation of residual stress is dependent upon many material and process factors, there are several other viable mechanisms (using thermal, mechanical or phase transformation effects) by which it may be modified. It is only now, using relevant advances in numerical and experimental methods, that these techniques are being fully explored. This article gives a brief introduction to weld-induced residual stresses and reviews the current state-of-the-art with regard to their reduction. Emphasis is placed on the recent development of unconventional techniques, and the mechanisms by which they act.

Keywords: Welding, residual stress, residual distortion, stress relief.

Introduction

Macro-scale residual stresses, which equilibrate internally over a component or assembly, are ubiquitous in everyday life. They allow tempered glass to resist fracture by inhibiting the propagation of cracks at the material's surface. They keep common fasteners such as nails and screws from slipping free by exerting a contact force at the interface of the different components. They even act within our own bodies to brace our arteries against the pressure of our blood¹. However, adverse distributions of residual stress in engineering components (specifically, high tensile stresses in areas prone to fracture or fatigue), can lead to unexpected or premature failure [1]. The formation and relaxation of residual stresses during manufacturing processes also causes unwanted and problematic deformation which can be costly to correct. The large amount of non-uniform heat input inherent in most forms of welding generates characteristic distributions of residual stress which tend to have particularly adverse mechanical effects. This makes welding a frequent cause of residual stress problems in engineering practice.

Broadly, residual stresses can be categorised into three groups based on scale [2]. Type I stresses, which exist in the macro- scale, are most frequently of concern to engineers [3]. In polycrystalline materials, inter-granular scale Type II stresses are generated by mechanical incompatibility between adjacent crystallites [4]. Type III stresses, on the inter-atomic scale, result from crystallographic defects [3, 5, 6]. With the greatest immediate implications for engineering design, only Type I stresses resulting from welding process will be discussed here.

¹ Mammalian arteries have been shown to contain circumferential residual stresses which are compressive at the inner arterial wall, and tensile at the outer wall. This is believed to make the total distribution of stress in the artery more uniform when the vessel is internally pressurised *in vivo* [163].

Formation of residual stresses during welding

Due to their widespread occurrence and notorious effects, weld-induced stresses are the prototypical example of detrimental residual stress in structural materials. The formation of residual stresses during welding is a consequence of the fact that different parts of a welded object experience different cycles of thermal expansion and contraction. The resulting thermal stress causes a non-uniform distribution of irreversible material deformation, and some of this deformation remains after the material has cooled, resulting in an internal and completely self-equilibrating stress field.

Residual stress formation during welding is illustrated schematically in Figure 1. Most forms of welding require a large amount of localised heat input at the joint interface to achieve material bonding, which occurs by mixing in a liquid or partially-melted state, or by solid-phase diffusion² [7]. Inevitably this elevated temperature causes thermal dilation of material, accompanied by a gradual decrease in yield strength and eventually, in the case in fusion welding, melting. By contrast, material remote from the weld seam remains at a relatively low temperature throughout (see Section B-B in Figure 1). The heated material at the interface then begins to cool, and any liquid metal solidifies. The material then cools and contracts as a solid, but is mechanically constrained by the surrounding cold material (Section C-C). This results in a characteristic distribution of residual stress, with very large tensile stresses in the region of the joint (where material is prevented from contracting as much as it otherwise would) which are balanced by compressive stresses elsewhere [5, 8, 9].

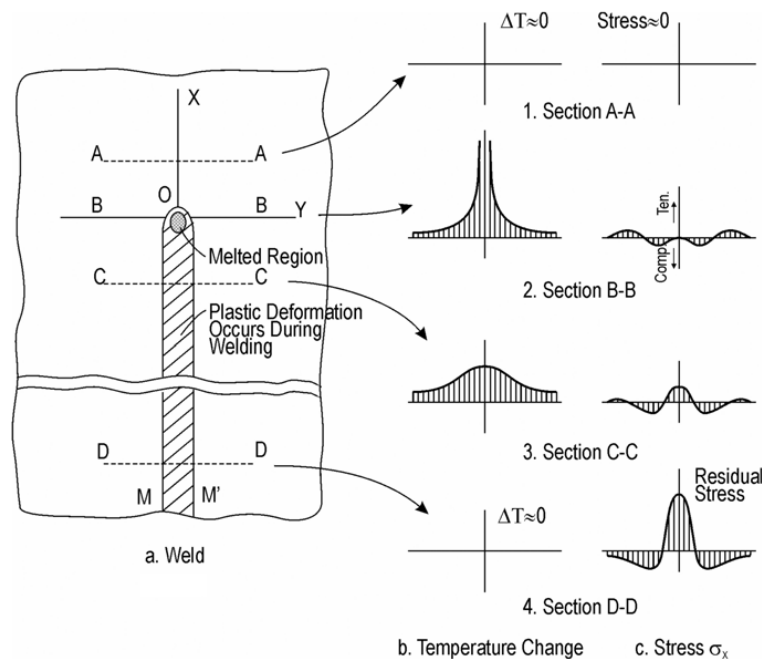


Figure 1: The process of residual stress formation in a weld [10].

The exact magnitude and orientation of the resultant residual stresses depends on the direction of the greatest thermal gradients encountered as the material cools, and on the mechanical constraint

² Welding processes which involve complete melting of some part of the material are known under the umbrella term of 'fusion welding'. This encompasses most common welding methods, but excludes solid-state processes such as linear friction welding and diffusion bonding.

applied to the cooling weld metal. A simple example is shown in Figure 2a: in a mechanically-unconstrained linear weld, the largest thermal gradient typically occurs across the transverse direction. Material can therefore contract freely in this direction since the contraction is approximately uniform along the length of the weld. Correspondingly, in the out-of-plane direction the weld metal is unconstrained, and therefore free to contract. However in the *longitudinal* direction, contraction is impeded by the surrounding cold material. Consequently, the largest tensile component of residual stress in a weld of this type is almost always oriented in the longitudinal direction. In other situations, for example for welds in thicker material and on objects of greater complexity other residual stress distributions may arise, but they are always determined by the pattern of thermal contraction and mechanical constraint³. Figure 2b shows an example of a more heavily-constrained weld. In this case, the more rigid mechanical boundary conditions imposed on the contracting weld metal mean that large tensile residual stresses may arise in the transverse direction, as well as the longitudinal.

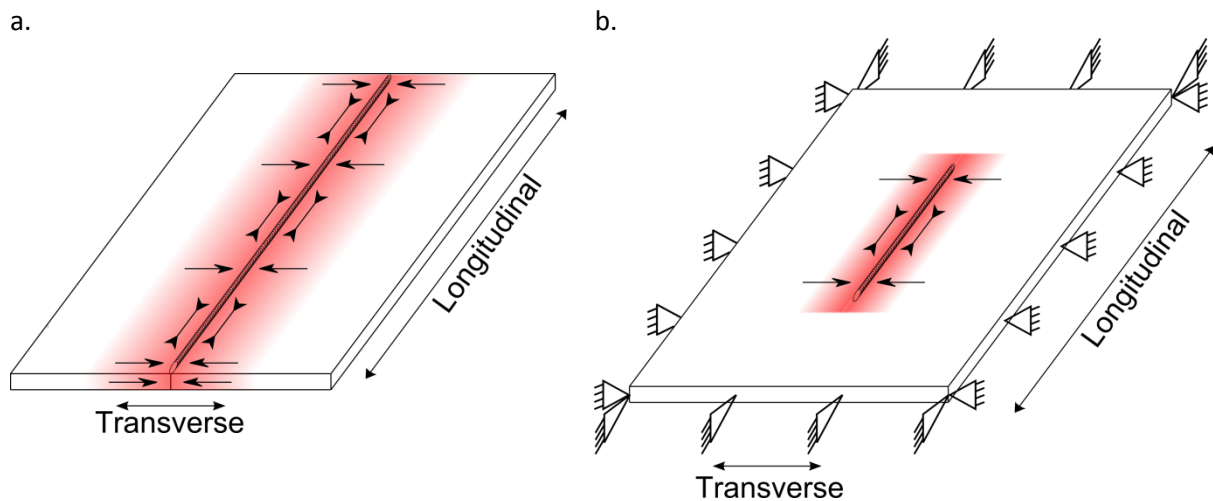


Figure 2: Thermal contraction (indicated by arrows) during the cooling of linear welds: a. unconstrained butt weld, b. bead-on-plate or repair weld, where the surrounding material or structure provides mechanical constraint.

The peak tensile residual stress observed at the centre of a fusion weld can approach the yield strength of the unaffected parent material, or even exceed it wherever there is hardening of the weld material due to compositional or microstructural change [9, 11]. However, the actual magnitude depends on the thermal field and the properties of the material, specifically its strain-temperature and yield stress-temperature relationships [12]. For example, in aluminium alloy welds the development of tensile stresses at the weld interface is normally limited by the low elevated-temperature yield stress and low post-weld hardness compared with the parent metal (see Figure 3), resulting in a characteristic ‘M-shaped’ tensile stress profile [13, 14]. However, in fusion welds the total size of the tensile region is typically larger than the extent of the melted zone (Figure 3), corresponding instead to the extent of plastic deformation induced by thermal stress. Consequently, welding with a greater heat input generally results in a wider tensile region [11, 15].

³ The distributions of residual stress found in other types of weld geometry are discussed by Leggatt [9].

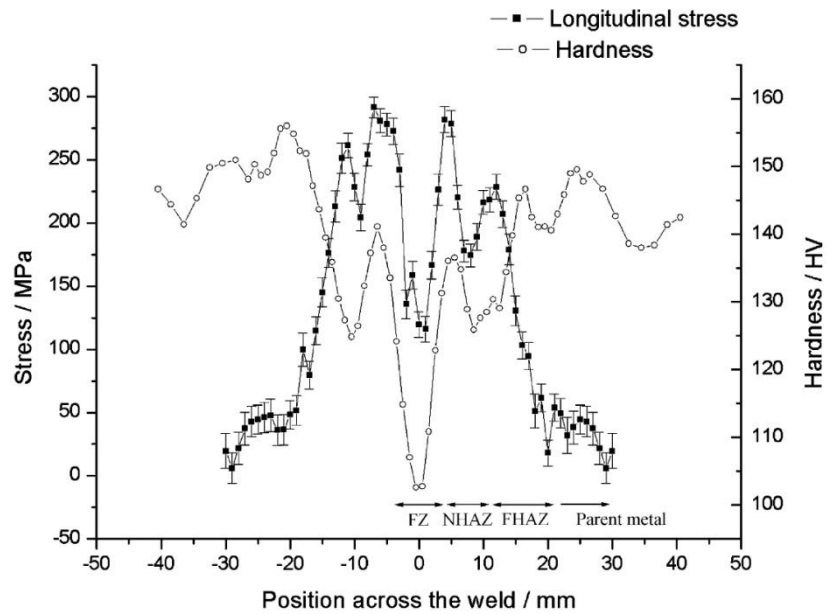


Figure 3: Comparison of longitudinal residual stress (measured using neutron diffraction) and hardness in a gas metal arc weld in 2024 aluminium alloy. Widths of the weld fusion zone (FZ), near heat-affected zone (NHAZ), far heat-affected zone (FHAZ) are indicated. The magnitude of the residual stress in the weld is limited by the variation in yield strength brought about by the thermal effects of welding [16].

While simple in concept, residual stress formation in welds is quite difficult to predict quantitatively. The main problem is that since the process includes coupled thermal and mechanical components, the number of input variables involved is large [17]. A list of factors affecting residual stress would include: the geometry of the welded object, its thermal history, its (temperature-dependent) material properties, its phase transformations and metallurgical phenomena, and its mechanical boundary conditions. Over the last forty years, researchers have used numerical models of increasing complexity to study the process. Today, the use of the finite element method is dominant and modelling of welding residual stresses can be considered a relatively mature field, which finds substantial industrial application [18]. An example finite element mesh for a welded object is shown in Figure 4.

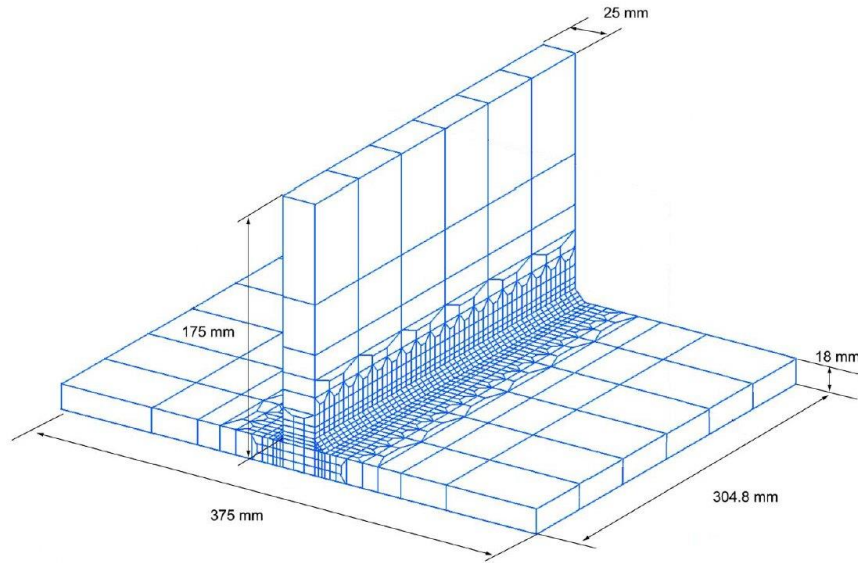


Figure 4: Finite element mesh for modelling of residual stress formation in a welded T-joint [19]. Note that the mesh density is much greater around the weld seam, where large temperature and deformation gradients are expected.

Despite recent advances in computing power, in most practical cases it is necessary to take advantage of the fact that the coupling between some of the different physical processes involved is quite weak (see Figure 5), by solving these different parts of the problem separately [18, 20]. For example, in an arc weld the heat generation due to material plasticity and viscoelasticity is usually small compared with the thermal energy transferred by the arc, i.e. the mechanical process only weakly affects the thermal one. However, the thermal field has a large mechanical effect via thermal dilation, so most models calculate the complete temperature history first, ignoring internal heat generation, and then use this to determine mechanical effects. By extending this concept and using judicious consideration of the coupling between different physical processes, it is also possible to consider mechanical and material changes at different length scales and throughout consecutive manufacturing processes: recent examples of this have been discussed by Hattel [21]. Introductions to contemporary weld modelling methods are given by Michaleris [20], Lindgren [18, 22] and Goldak and Akhlaghi [23], while further discussion of the formation of residual stress during welding can be found in the textbooks by Masubuchi [24] and Radaj [25], and an introductory article by Nitschke-Pagel and Wohlfahrt [26].

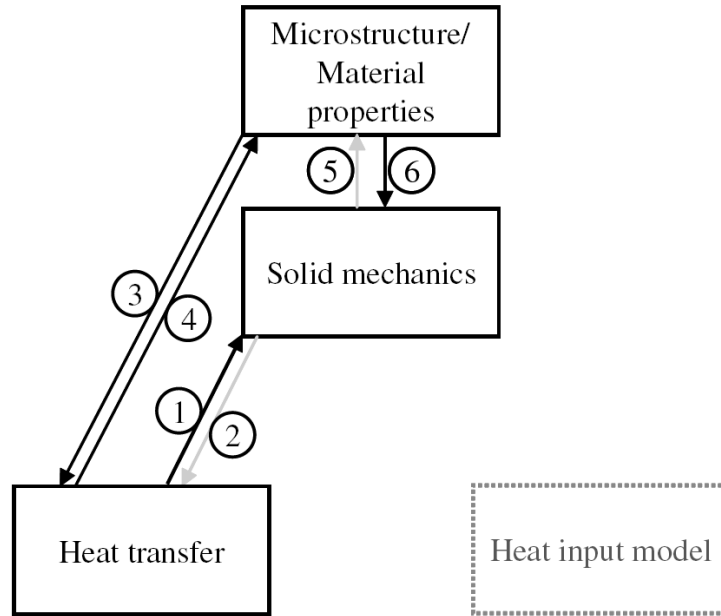


Figure 5: Coupling between the different physical processes involved in thermo-mechanical modelling of a weld. Strong couplings are indicated by black arrows, while weaker couplings are grey. 1. thermal expansion causes deformation, 2. heat generation due to irreversible deformation changes temperature, 3. latent heat and material thermal properties affect heat transfer, 4. temperature affects microstructure, 5. deformation affects microstructure, 6. mechanical properties depend on microstructure [18].

Effects of welding residual stresses

Of the many mechanisms which can lead to material failure, most are affected by the presence of residual stress. A thorough review of this subject has recently been provided by Withers [2], but a few of the most important effects of welding-related stresses are outlined below.

Fracture and fatigue

Residual stress is known to affect both the static fracture and fatigue properties of welded joints. In general, the superposition of a residual stress field with one due to external loading modifies the stress intensity at crack tips and hence the crack driving force [27, 28, 29, 30]. Indeed, in the prediction of weld fatigue lifetimes, it is commonly assumed that the large tensile stresses which may be present in the weld region dominate over the effect of the mean stress applied during the loading cycle [31]. However, while residual stresses affect fully elastic fracture and high-cycle fatigue significantly, they have much less influence over ductile failure because they are rapidly accommodated by plastic deformation [32, 33, 34]. Several researchers have recently suggested that residual stress may also have a noticeable effect on ductile tearing resistance [30, 35], but currently the mechanism for this is unclear.

Fatigue cracks often initiate at an object's surface, and they require tensile stresses to propagate. Therefore, near-surface tensile residual stresses tend to accelerate fatigue cracking, while compressive stresses hinder it [36]. Consequently, many fatigue-life improvement methods such as shot peening and autofrettage rely on creating compressive residual stresses in areas most at risk. Of course, since residual stresses must be self-equilibrating, corresponding tensile stresses must also exist somewhere. In the example of shot peening, compressive stresses are only induced in a thin surface layer (typically < 1 mm) [37], while the corresponding tensile stresses form further into the material. Welding, by contrast, tends to result in large tensile residual stresses throughout the weld

thickness, which equilibrate with opposing stresses situated further away from the joint [38]. As a result of this, both methods which induce compressive surface stresses and methods which reduce stresses through the entire weld thickness may be used to improve fatigue life of welds.

As well as causing residual stresses, welding also causes microstructural change and geometric stress concentrations [39, 40, 41]. Both of these factors can also affect fatigue, which complicates the study of welding residual stresses with respect to fatigue life [42, 43]. Furthermore, residual stress distributions can themselves be changed by in-service loading conditions, generally by yielding during the first loading cycle [36, 44].

Stress corrosion cracking

Stress-corrosion cracking (SCC) is a form of environmentally-assisted material failure which occurs when the combined effect of chemical and mechanical driving forces causes gradual crack propagation throughout the affected material [45]. Since both chemical and mechanical factors are involved, only materials exposed to particular corrosive environments while under mechanical stress are susceptible to SCC. The residual stresses left behind by welding are often sufficient to initiate SCC in areas where it would not otherwise occur due to the lack of a sufficient mechanical driving force [46]. Furthermore, welding can also cause geometric stress concentrations and increased metallurgical susceptibility to corrosion [47], so SCC frequently initiates at welded joints. This causes serious problems in applications (such as gas pipelines and nuclear reactor components) where welded parts are used in a corrosive environment [48, 49], often necessitating costly inspection programmes to prevent this ‘insidious’ form of failure.

Distortion

By definition, the residual stress field within an object is internally self-equilibrating. For a stress distribution to exist in the absence of any externally-applied force or temperature differential, there must be an internal incompatibility in strain⁴ [50, 51]. Therefore, when residual stress is added or relaxed during any manufacturing process, there must also be a corresponding inhomogeneous deformation. Residual stresses due to welding, for example, are associated with strains which when accumulated along the length of a weld seam, can often cause visible warping of a welded object. This distortion is by far the most evident and frequently the most problematic effect of residual stress. Small residual strains due to plastic deformation at the weld seam cause different modes of distortion, originally categorised by Masubuchi [24], depending on the weld and object geometry. In addition to shrinkage and bending-type distortion modes, welds in thin-walled structures often produce residual stresses large enough to cause buckling, which can complicate distortion analysis and prediction [52].

The implications of welding distortion for manufacturing (aside from those related to other effects of residual stress) are of great practical concern [53, 54], and have led to the development of a host of techniques specifically to prevent distortion, without aiming to remediate the underlying residual stress. These include bending-back of distorted weldments, presetting [55], control of mechanical constraint [56, 57, 58], control of weld sequencing [53, 59, 60], and flame straightening. An example of the effects of varying mechanical constraint is shown in Figure 6, and such methods of distortion control are discussed further by Conrardy and Dull [61] and Masubuchi [24].

⁴ This incompatibility is variously referred to by researchers as ‘eigenstrain’, ‘inherent strain’ and ‘misfit strain’.

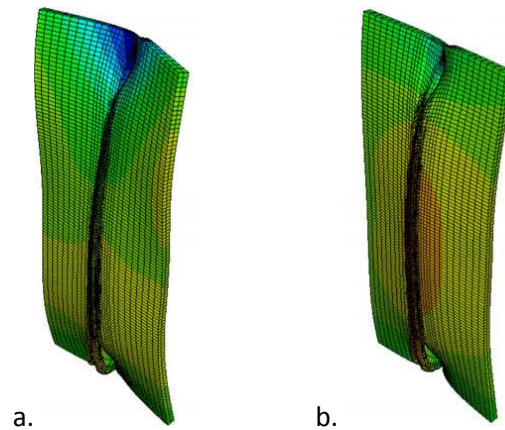


Figure 6: Predicted distortion of a dual-phase steel overlap weld with clamping released a. immediately after welding, b. once the weld has cooled to room temperature. Out-of-plane displacements magnified 50x [62].

Measurement

Techniques for measuring residual stress have been recently discussed by Rossini et al. [63] and Withers et al. [64], but briefly, three fundamental strategies exist:

1. Measuring the change in strain as residual stresses are relaxed by removal or cutting of material.
2. Measuring the inter-atomic spacing and comparing this to the spacing in an unstressed reference specimen.
3. Measuring the change in another physical phenomenon with which stress interacts.

Practical implementations of the first option include the hole-drilling method, in which stresses are back-calculated from strain measurements made near a small hole as it is drilled [65, 66], and the contour method [67], where accurate measurement of the profile of a cut face is used to reconstruct a map of the residual stresses before cutting. Of course, all such ‘relaxation’ methods are at least partially destructive to the sample; such techniques are the subject of a recent review by Schajer [68]. The second option is possible because the inter-atomic spacing in a crystalline material changes in response to applied stress – a fact which is reflected in the elastic strain response of the bulk material. Therefore, by using x-ray or neutron diffraction to measure the crystal lattice-spacing, strain can be measured non-destructively in (polycrystalline) metals and ceramics, and from this the stress state can be calculated. For the final method, it is possible to use changes in the sonic and magnetic properties of some materials to measure stress. For example, the configuration of magnetic domains in ferromagnetic materials is sensitive to stress, and so residual stresses can be inferred from (calibrated) measurements of magnetic Barkhausen noise [69]. However, the effect of residual stress on these properties is not well understood and is often relatively weak in comparison to the effect of other factors (eg. microstructure), so these techniques are normally used only for comparative measurements [1].

To measure residual stresses produced by welding, diffraction using neutrons or high-energy synchrotron x-rays is currently favoured by researchers. These methods have been developed to a point of practical and quantifiable accuracy, and can be used at a range of spatial resolutions conducive to the study of engineering structures. Furthermore, usable quantities of neutron or synchrotron radiation can penetrate deeply (in the order of tens of mm) into most common metals, and can therefore be used for measurement at locations which cannot be probed by other means (see Figure 7). Unfortunately, these methods can only be performed at a small number of neutron

and synchrotron facilities, and are therefore not suitable for common use in industry. Neutron techniques are discussed by Krawitz [70] and Withers [2], and synchrotron diffraction by Reimers et al. [71]. Diffraction of lower-energy x-rays (produced using conventional x-ray tubes [72]) is more widely used due to its accessibility and relative accuracy. However, a major drawback is that the penetration depth of this radiation is low, and so only stresses close to the surface of the material (conventionally, within a few tens of microns) may be measured.

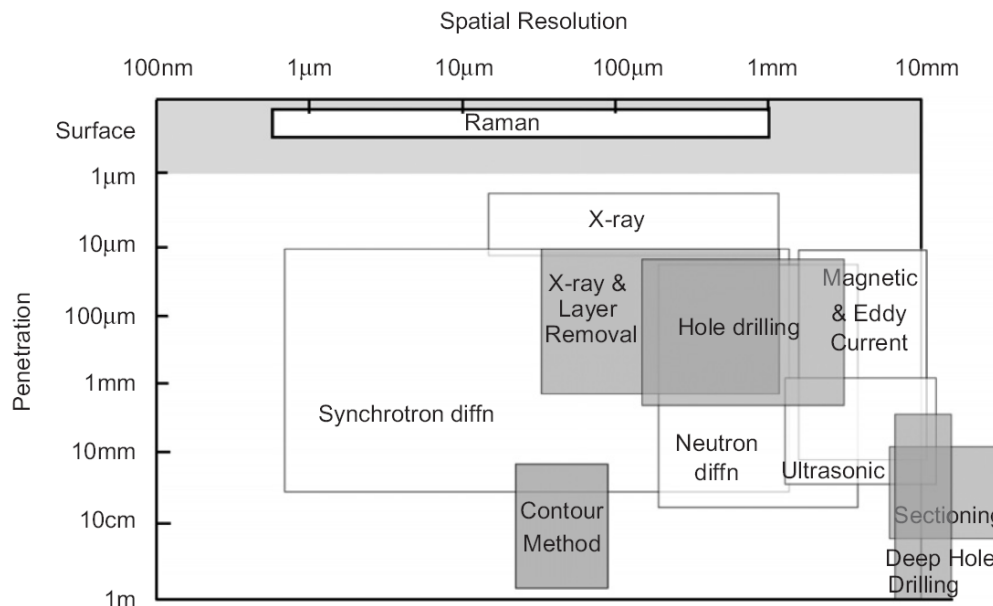


Figure 7: Approximate capabilities, in terms of spatial resolution and penetration depth, of different residual measurement techniques [64].

Reduction of welding residual stresses

Overview

A wide variety of techniques are available for the reduction or modification of residual stress distributions in bulk materials. Some of these, such as annealing and peening processes have been adapted or optimised for use on welded joints. However, there also exist welding-specific methods such as in-process cooling and Global Mechanical Tensioning (GMT), which are designed to work against the particular thermal strain mechanism of residual stress formation which exists in welding, or against the particular distributions of residual stress which welding produces. These methods have received increased attention over the past two decades, as researchers seek cheaper and more effective alternatives to long-standing techniques.

To cause a change in the residual stress state in an object, a permanent plastic deformation must be introduced, or the occurrence during welding of such a deformation must be influenced. This can be done by using an externally-applied mechanical force, by the application or modification of a thermal field, or by inducing a solid-state phase transformation. It is therefore possible to categorise residual stress modification strategies into three broad groups based on these three mechanisms of action. Here, welding residual stress mitigation methods have been further categorised into 'conventional' techniques, which currently see widespread application, and 'advanced' techniques which are mainly at the experimental stage of development and not commonly encountered outside of research. Additional reviews of the application of stress engineering techniques to welding can be

found in works by Radaj [25], Feng et al. [73], Withers [1], Williams and Steuwer [74], and Altenkirch [75], while a helpful guide to early work on the topic from the USSR is provided by Pavlovsky and Masubuchi [76].

Conventional thermal techniques

Post-weld heat treatment

Stress-relief annealing involves heating an object uniformly, normally to several hundred degrees above ambient temperature, to allow residual stresses to relax automatically. Application of this procedure to welded joints, which is known as Post-Weld Heat Treatment (PWHT), is a very commonly accepted method of residual stress relief and has been shown to be effective for this purpose under a wide range of circumstances [77, 78, 79, 80, 81]. Primarily, the reduction in yield strength at high temperature causes the material to yield locally under its own internal stresses, however it is also believed that in many cases additional deformation can be caused by creep and recrystallisation [82, 83, 84]. After the stress has been relaxed, gradual and uniform cooling is used to prevent subsequent stress formation. Depending on the material, sufficient stress-relief may take place at below the temperature required for any change in microstructure, but typically diffusional processes or even gross recrystallisation will also occur [1, 25]. Often this is a welcome side-effect; in carbon-manganese steel weld zones containing brittle phases (particularly martensite) generated during rapid cooling of the weld metal, tempering which occurs during PWHT can act to restore fracture toughness.

Though it is effective at reducing residual stress in most bulk metals, PWHT is not universally applicable. For example, PWHT is not normally applied to precipitation-hardening alloys due to the risk of over-aging the parent metal⁵: temperature-controlled diffusion acts to coarsen the precipitate distribution, reducing the precipitate's effectiveness at impeding dislocation movement. Likewise, in dissimilar-material welds, mismatch between different thermal expansion coefficients can cause PWHT to be ineffective, or even detrimental [85, 21]. The application of PWHT can also cause a form of brittle failure known as stress-relief cracking or reheat cracking, in which thermally-induced embrittlement leads to cracking as high-temperature yielding or inter-granular creep occurs [86]. Finally, the process becomes both expensive and time-consuming when large components are involved.

Control of heat input during welding

The energy input per unit length of weld made obviously has a pronounced effect on the distribution of temperature in the material [87]. This can in turn affect both the weld microstructure and the formation of residual stresses. Unfortunately, the need for a sufficient temperature at the joint interface to allow material bonding puts a practical limit on the amount by which heat input can be reduced. The heat input is further constrained by factors relating to the welding process itself: in laser welding for example, reducing the heat input will eventually cause transition of the process from keyhole to conduction mode⁶. Therefore, control of welding heat input can never completely

⁵ The weld itself and the surrounding heat-affected zone will typically be over-aged anyway after the welding thermal cycle.

⁶ There are normally considered to be two distinct modes of laser welding. In keyhole mode, continual vaporisation opens a 'keyhole' in the material, which allows a very deep and thin weld cross-section. In conduction mode, material vaporisation is insufficient to sustain a keyhole, resulting in a wide and shallow weld [164].

prevent residual stresses from forming, but it can reduce the width over which plastic strain (and hence tensile residual stress) occurs [11, 15].

Uniform preheating of the weld region is widely employed to reduce the large thermal gradient necessary to enable fusion at the weld interface, which is the cause of three common problems: 'hot cracking' (thermal fracture which can occur during the welding of brittle materials), the formation of brittle martensite due to rapid cooling of the weld material, and residual stress. Preheating the weld region may also be used to dry the surface of the material, which is sometimes necessary to prevent hydrogen embrittlement - a common symptom of excessive hydrogen absorption in high-strength steel welds [88]. However, due to the decreased yield strength of the parent material at elevated temperature, preheating can also allow increased plastic deformation, having a detrimental effect on residual stress [89]. Therefore, though it may reduce residual stresses in some material/thermal cycle combinations, preheat cannot be considered a universally effective method of residual stress control.

Conventional mechanical techniques

Peening

Peening describes a set of dynamic processes which use impact or the propagation of shock waves to cause deformation. The object of applying peening to a surface is to create an inherent strain which results in a compressive state of residual stress there. This compressive state of stress is equilibrated by tensile stresses deeper within the bulk of the material. While hammer and shot-peening of welds have long been practiced, similar treatments such as needle, ultrasonic and laser shock peening are becoming more widespread [90, 91]. As in many other applications, peening is used to improve the fatigue life of welded joints, since the compressive residual stresses which it introduces inhibit fatigue crack propagation from the material's surface [92, 93, 94]. Impact indentations can also smooth imperfections in the shape of the weld toe (see Figure 8), reducing stress concentrations and hence further increasing fatigue life [95].



Figure 8: Ultrasonic peening being applied to a steel weld toe [91].

Due to their impactive nature, and the need for stresses to equilibrate over the thickness of the peened object, peening processes typically produce a compressive stress distribution only to a limited depth of penetration [37, 91, 96]. Since residual stress due to welding usually exists

throughout the thickness of the joined material, peening cannot normally be said to remove welding residual stresses but rather to superimpose an additional, protective residual stress distribution. Consequently, peening does not protect against crack propagation from internal defects, and residual stress which exists deeper in the material may still cause distortion of the welded object.

Vibratory stress relief

The difficulty and cost involved in applying PWHT, especially to large assemblies and castings, led to the development of Vibratory Stress Relief (VSR) during the Second World War [97]. In this method, the welded object is simply vibrated strongly using motorised or electromagnetic equipment. Despite many years of research, there is still disagreement over the fundamental mechanism by which this acts to reduce stresses, or indeed whether it has any significant effect at all [98, 99]. It has been proposed that VSR provides a driving force for dislocation movement at the intra-granular level [100], or even that it initiates a martensitic transformation in steels [101]. However currently the most widespread view is that under some conditions, VSR is able to cause local plastic deformation in the regions of material which, due to the presence of residual stress, are already close to their yield point. This theory explains both the gradual nature (i.e. occurring over many vibration cycles) of observed strain changes, and the apparent presence of a critical vibration amplitude, under which no stress relief will occur [102, 103, 104]. One implication of this idea is that cyclic plasticity occurs during the process, which might negatively impact the subsequent fatigue lifetime of any treated component. Despite recent advances in residual stress measurement techniques there is still a lack of published data on the topic of VSR, and so although VSR has many industrial users its efficacy and theoretical basis remain controversial.

Advanced thermal techniques

Localised cooling

By manipulating the distribution of temperature in a component as it is welded, localised cooling aims to modify or generally reduce the final pattern of residual stress. The earliest experiments were carried out in the 1960s in support of NASA's Saturn programme [105]. Although several cooling arrangements have been suggested, most modern experimenters have used an intense heat sink trailing the welding heat source to create a characteristic valley-shaped temperature distribution⁷ [106, 107, 108, 109, 110], shown in Figure 9. An example of a cooling device designed to achieve this is shown in Figure 10. Guan et al. [111] originally proposed that this can prevent the formation of a single wide region of tensile residual stress at the weld line, instead creating a more complex distribution of stress consisting of several local maxima and minima. The mechanism of thermal strain by which this comes about was subsequently explained by van der Aa et al. [109] and Richards et al. [110], using numerical modelling.

⁷ Following the convention of Guan et al. [165], this process is alternatively referred to as Low Stress No Distortion (LSND) welding.

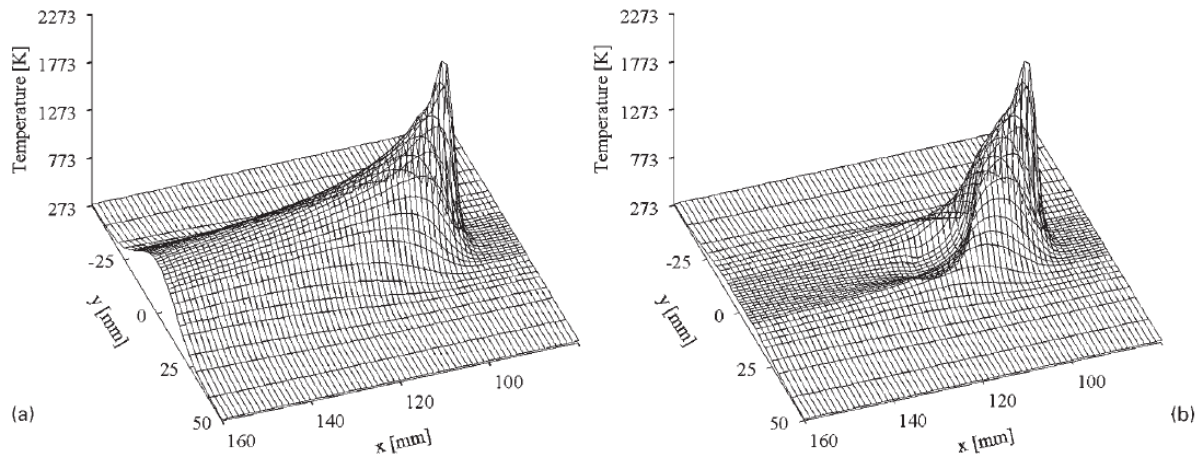


Figure 9: Simulated temperature distributions in thin aluminium alloy sheet: a. conventional arc welding, and b. arc welding with a trailing heat sink [109].

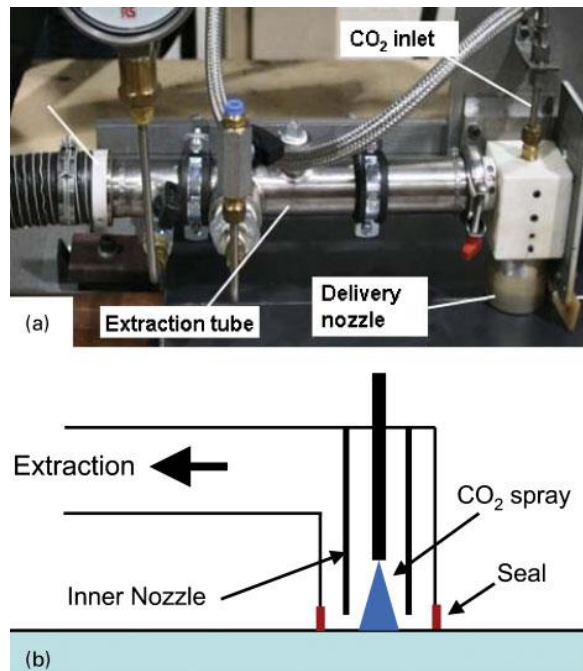


Figure 10: Nozzle arrangement for cryogenic cooling of the weld seam during welding, allowing continuous delivery and extraction of CO₂ spray [110].

Efforts to model the process agree that relief of residual stress is greatest with a very localised and intense cooling source, positioned as close behind the welding heat source as possible (see Figure 11) [109, 112, 113, 110]. Various researchers have used different cooling media: solid CO₂ 'snow' [114, 115, 116] and argon-atomised water [107] have featured in recent studies. Liquid nitrogen has also been suggested as a suitable coolant [110, 117], however it does not appear to have been tested experimentally in any study to date. Further reviews of available literature on in-process cooling are given by Bagshaw et al. [118], van der Aa [116] and Richards [119].

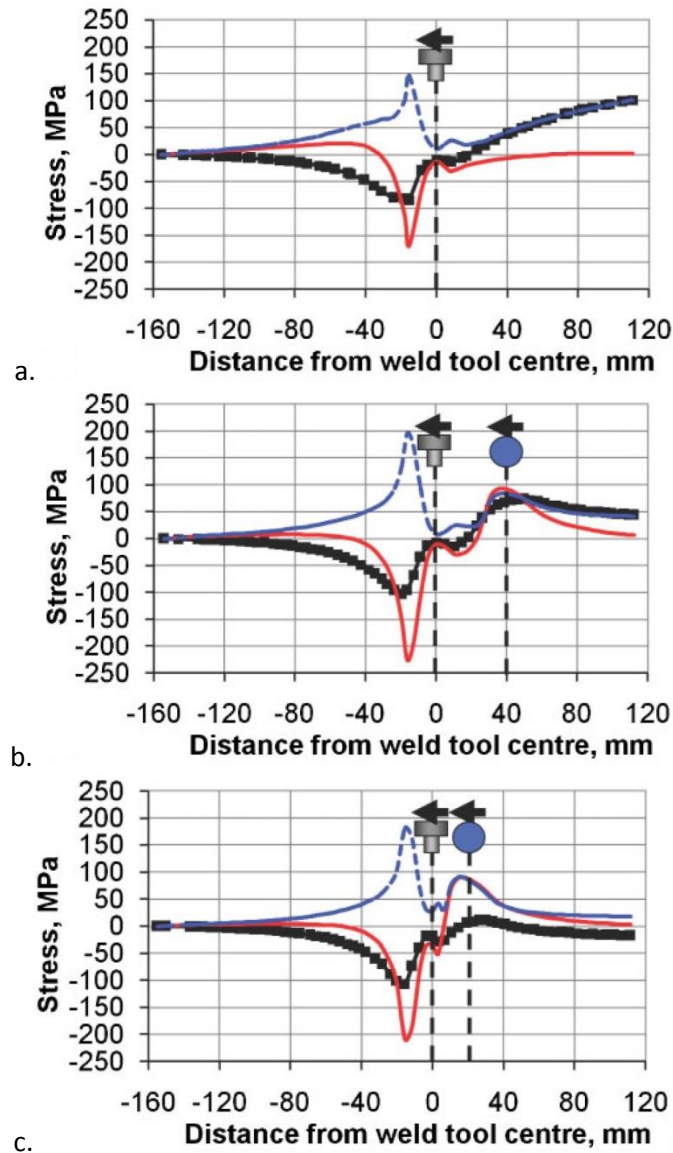


Figure 11: Effect of cooling source position on stress development during friction stir welding of aluminium alloy with localised cooling: a. no cooling, b. trailing the welding tool by 40 mm, c. trailing by 20 mm. The black line with squares represents the longitudinal component of stress, the solid red line is the transverse component, and the dashed blue line is the von Mises stress [110].

Localised heating

As with localised cooling, a number of schemes of in-process heating have been investigated, with the intention of modifying the stress distribution in the vicinity of the welding heat source [120, 121]. Most researchers describe how the process creates a tensile stress in the longitudinal direction during welding⁸ [122, 123, 124]. The presence of a tensile stress during welding, and its subsequent removal due to temperature equilibration, has a similar effect to GMT (see section on GMT below); reducing the longitudinal strain misfit between the weld material and the parent metal. An alternative mechanism was first investigated by Greene and Holzbaur, who pioneered this form of stress-relieving during the latter part of the Second World War [125]. They used localised heating adjacent to the weld after it had been completed to overstress the weld material - yielding it, and removing the tensile residual stress (Figure 12c).

⁸ For this reason, localised heating methods are often alternatively described as 'thermal tensioning' by some authors.

In practice, thermal tensioning can be carried out either by creating a transverse thermal gradient simultaneously along the entire length of the weld ('steady-state thermal tensioning', Figure 12a), or by using moving heat sources to create a stressed region around the welding tool only ('transient thermal tensioning', Figure 12b) [126]. For transient tensioning, a suitably intense heat source is required, and various researchers have investigated the use of flame heaters [122, 124, 126], laser spots [113, 120], and induction heaters [127] for this purpose. Of course, in all cases the mechanism by which the stress state in the weld is changed (via thermal dilation of part of the material), is fundamentally the same. Reporting of the level of residual stress reduction achievable using this method has been quite mixed, however, ranging from 21-32% [122] to 74% [128] in experimental studies.

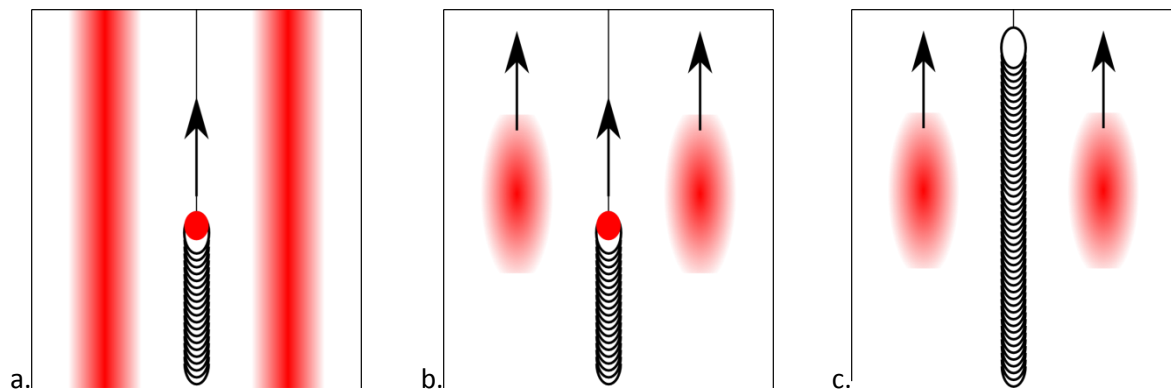


Figure 12: Localised heating methods: a. steady-state thermal tensioning, b. transient thermal tensioning, c. post-weld thermal overloading. The welding arc (red circle) and additional heated regions (diffuse red areas) are shown.

Advanced mechanical techniques

Rolling

Through the application of a large compressive force to the material's surface, localised high-pressure rolling of welded joints causes yielding of metal in the weld region, relieving the large residual stresses which exist here [129, 130, 131, 132]. In most systems, this is achieved using a single narrow roller applied directly to the weld line, with the material backed by a rigid surface; an example of this arrangement is shown in Figure 13. However, rolling the weld seam between a pair of rollers has also been described [129, 133, 134, 135, 136]. An obvious limitation of the process, therefore, is that both sides of the weld must be accessible so that the underside of the weld may be supported during rolling.

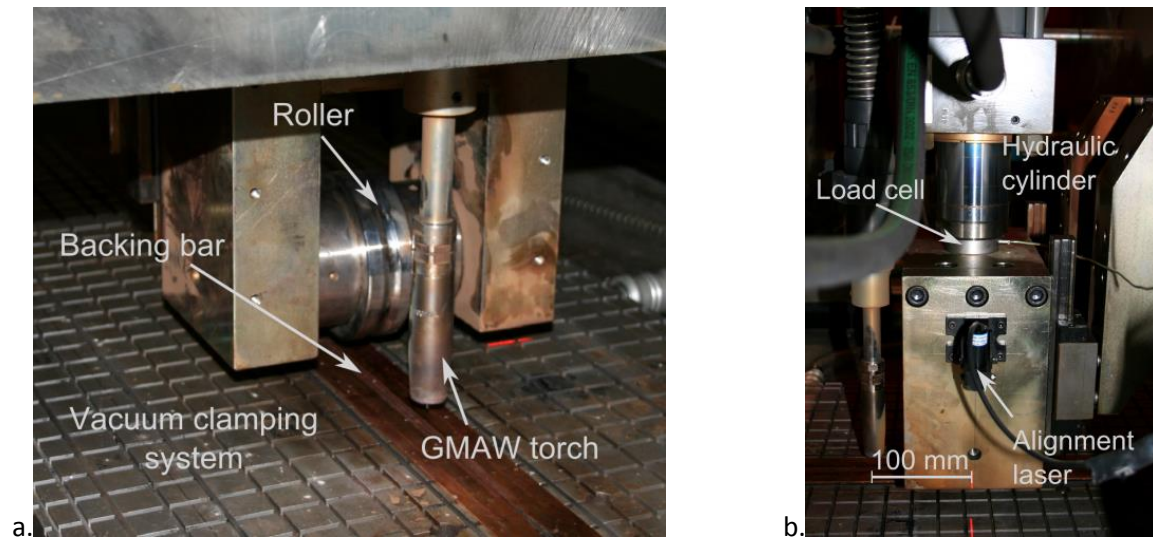


Figure 13: Experimental apparatus for rolling of gas metal arc welds (GMAW) [137].

Both rolling *in situ* (i.e. during welding), and post-weld have been studied. Recent experimental and modelling studies indicate that post-weld rolling gives a far greater reduction in the residual stress field [131, 132, 137, 138]; this is because after *in situ* rolling, residual stress continues to form during the subsequent cooling [137]. A comparison of residual stress distributions resulting from post-weld and *in situ* rolling is shown in Figure 14. The temperature of the rolled material does however determine both the amount of plastic deformation that is possible for a given roller load [75, 136], and the material microstructural response to the process [139, 140, 141, 142]. A future application of *in situ* rolling may therefore be to improve weld microstructure by hot deformation. It has been suggested that tandem systems for *in situ* rolling, where the first roller produces a large deformation at high temperature and the second work-hardens the material when it is cooler, may be advantageous. While this method was investigated by researchers working in the USSR, it has not been attempted in any recent work [140, 141].

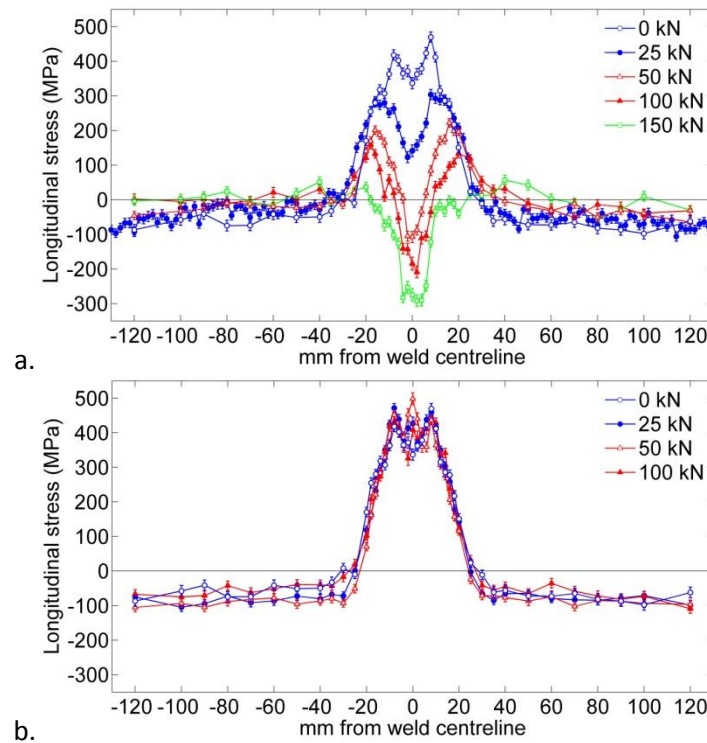


Figure 14: Cross-sectional distributions of longitudinal residual stress in welded low carbon steel plates treated with rolling at various levels of roller force: a. post-weld rolling, b. *in situ* rolling [137].

Global mechanical tensioning

Global Mechanical Tensioning (GMT), shown in Figure 15a, involves stretching material in the direction of the weld line to cause a longitudinal tensile stress throughout it during welding [143, 144]. The mechanism by which this reduces the residual stress is summarised by Richards et al. [13, 119]. Essentially, the magnitude of the tensile longitudinal stress which can exist at the weld is always limited by the yield strength of the weld material. By tensioning the surrounding material to an appreciable fraction of this, the mismatch in strain between these two regions can be reduced or even reversed. When the tensioning is released after welding, this results in a corresponding reduction in residual stress.

Depending on the longitudinal tensioning load used, GMT can greatly reduce residual stresses at the weld line, or even introduce compressive stresses in this region [145, 146, 147, 148], see Figure 15b. For welds in 2000-series aluminium alloy, the magnitude of tensioning stress that must be applied during welding to reduce the longitudinal residual stress to approximately zero, has been reported as 25-40% of the room temperature yield stress of the parent material [146, 148]. GMT therefore requires expensive tensioning equipment to apply this large force. Additionally, since the force needs to be applied in the same direction as the weld line, application to complex welds would be very difficult. Consequently, the applicability of GMT to practical industrial processes has not yet been demonstrated [145].

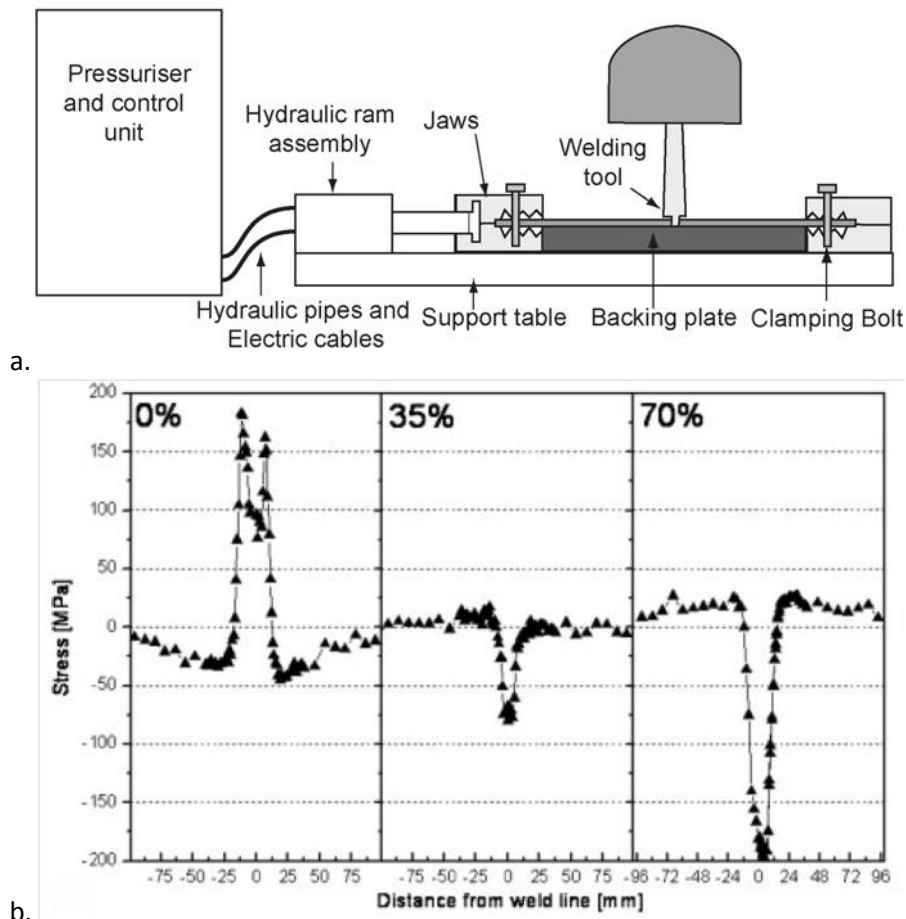


Figure 15: a. Equipment for GMT, b. longitudinal residual stress in three aluminium alloy friction stir welds with GMT at different levels of tensioning (synchrotron x-ray diffraction measurements). The magnitude of the applied stress is given as a percentage of the room-temperature yield stress of the parent material [146].

Weld material transformations

Transformations between different solid material phases are often accompanied by significant deformation. Consequently, transformations encountered during the welding thermal cycle can significantly affect the formation of residual stress [149, 150]. A discussion of the stress/microstructure relationship in the context of welding is given by Bhadeshia [151]. The effect was investigated in the 1970s by Satoh [152] and Jones and Alberly [153], who measured the stress induced in constrained steel specimens as a thermal cycle was applied. Of particular interest are the austenite \rightarrow martensite and austenite \rightarrow bainite transformations; these displacive transformations, which (in carbon steels) often occur during the cooling of the weld metal, are associated with a dilational strain that can be used to counteract the thermal contraction which causes tensile residual stress⁹.

To prevent the accumulation of tensile residual stresses, the material of the weld must be carefully chosen so that it undergoes a transformation at the correct point in the thermal cycle. It is generally

⁹ During both the martensitic and bainitic transformations the shear component of lattice deformation is far greater than the dilational component (approximately 0.25 versus 0.03)[166]. During the formation of bainite, it has been shown that in addition to the relaxation of tensile stresses by dilational lattice deformation, there is also preferential growth of the new phase in crystallographic orientations which accommodate the applied stress [157, 167, 168]. This allows the shear component to influence the stress state too, however the extent to which this may be deliberately controlled is not currently known.

taken that the transformation should occur at a temperature low enough to preclude subsequent build-up of stress, but should be complete by the time the metal cools to room temperature¹⁰ [154, 155]. Figure 16 shows schematically the effect of different phase transformations on the build-up of stress in uniaxially-constrained steel specimens as they are cooled from 1000°C. The austenite → ferrite transformation (a) takes place at too high a temperature to have a great effect on the residual stress: thermal contraction continues after the transformation, and the tensile stress resulting from this saturates at the yield strength of the material. On the other hand, lines (b) and (c) show the effect of bainitic or martensitic transformations taking place at a lower temperature. In both cases, while the transformation is complete by the time the material has cooled to room temperature, varying the transformation temperature affects how much thermal contraction can occur subsequent to transformation.

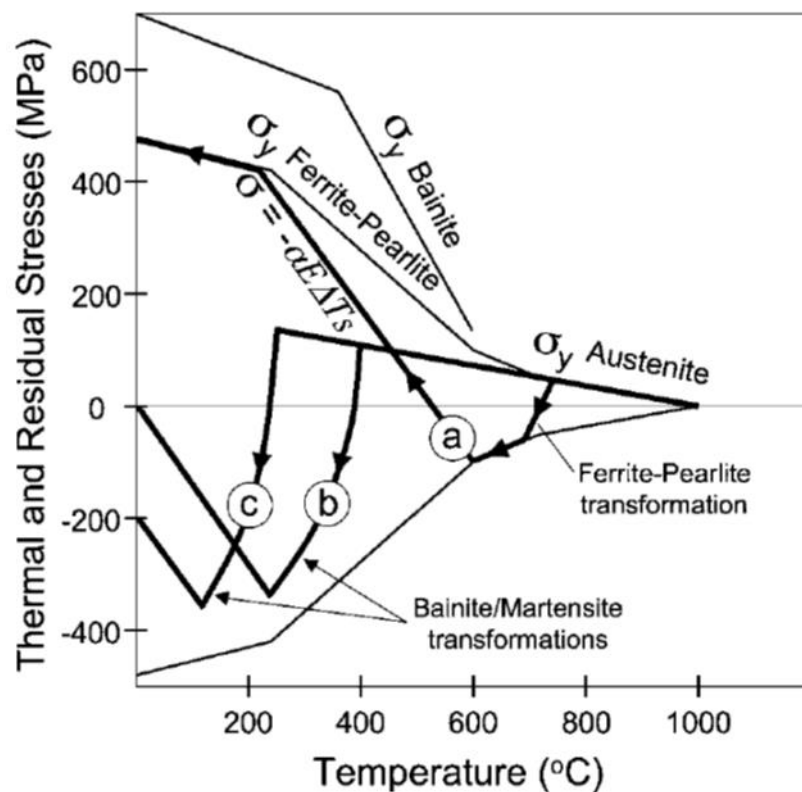


Figure 16: Thermal stress development during the cooling of axially-constrained specimens of different steels: a. is ferritic-pearlitic, whereas b. and c. exhibit bainitic or martensitic transformations (from Francis et al. 2007 [46], after Nitschke-Pagel and Wohlfahrt 2002 [26]).

Since the majority of common welding processes involve the addition of filler material at the joint interface, there is an opportunity to take advantage of transformation effects at the interface only, without changing the material used for the rest of the welded structure. Recently, there has been a concerted effort to design weld filler metals which reduce residual stress while maintaining acceptable mechanical properties. Most researchers have concentrated on the martensitic transformation, using additional carbon and/or a combination of nickel and chromium (in quantities up to about 15 wt% each) to reduce the temperature at which martensite begins to form [156, 157,

¹⁰ Although an incomplete martensitic transformation is not necessarily detrimental to the residual stress state, large amounts of untransformed austenite could seriously reduce the material's mechanical properties [169].

158]. Unfortunately, the increased carbon content and presence of brittle martensite can give low-transformation-temperature weld material reduced impact toughness [155]. Therefore, while the effectiveness of this approach for reducing residual stresses has been demonstrated in several studies [155, 157], further research is needed to simultaneously achieve excellent mechanical properties. A final important limitation of low transformation temperature materials is that they can undergo significant transformation strain when reheated, the effects of which would have to be carefully considered if such materials were ever to be used in elevated-temperature service.

Discussion

Mechanisms of stress reduction

The fundamental physical phenomena (such as thermal transport, solid mechanics and phase transformation) which underpin the formation of welding residual stress are individually well-understood. The complex interaction of these processes during welding is difficult to observe and predict, but at the same time means that there are number of possibilities available for residual stress reduction. Consequently, it has been seen here that thermal, mechanical and phase transformation mechanisms can be used to affect the residual stress state in a welded joint. However, in the case of most materials none of these mechanisms are fully independent of the mechanical properties: thermal methods can change the proportion of metastable phases present, cold deformation causes strain hardening [131], and methods based on filler metal transformations normally require a change in both the phase fraction and material composition away from their ‘ideal’ values (see Table 1). It is therefore likely that as research into residual stress reduction progresses, there will be continued specialisation of these different methods towards different material applications. For example, mechanical deformation is well-suited for use on low carbon steels since these do not strain-harden excessively. Localised cooling methods, by contrast, could cause unwanted formation of brittle martensite in some steels, and are therefore more suited to materials where this problem does not occur, such as Al-Cu alloy [116].

Table 1: Simplified overview of the metallurgical side-effects of welding residual stress reduction processes.

Class of process	Material parameters changed	Physical strengthening mechanisms most affected
<i>Thermal</i>	<ul style="list-style-type: none"> • Phase fraction • Microstructure 	<ul style="list-style-type: none"> • Precipitation hardening • Transformation hardening
<i>Mechanical</i>	<ul style="list-style-type: none"> • Dislocation density 	<ul style="list-style-type: none"> • Strain hardening
<i>Phase transformation</i>	<ul style="list-style-type: none"> • Chemical composition • Phase fraction • Microstructure 	<ul style="list-style-type: none"> • Transformation hardening

Current state of the art

Ideally, designers of welded assemblies would have techniques at their disposal which could reduce the residual stress field effectively to zero, or induce any state of stress deemed beneficial (for example, to impart increased fatigue resistance), while being both cost-effective and versatile. Much of the progress which has been made towards this in recent years can be attributed, at least in part,

to advances in both numerical and experimental methods - especially the use of neutron and synchrotron diffraction for residual stress measurement [31]. However, accurate quantitative analysis of residual stress in welded objects remains a non-trivial problem. This means that generating 'feedback' for the design process of any stress-reduction technique is time-consuming and costly.

There is also no perfect way of introducing the inherent strain required to change the residual stress state. It is evident that some of the methods discussed above, especially those based on manipulation of the thermal field, are difficult to control finely. Most are also difficult to bring to bear on stresses deep inside material, and can also have potentially detrimental effects on material properties. To compound this issue, stress is not a simple scalar quantity, but a tensor with six independent components varying over three spatial dimensions [159]. Therefore, imposing a desired residual stress in a particular direction or location may result in an undesirable one elsewhere.

Industrial awareness of welding residual stress has always been high. This can be attributed to the very visible nature of the distortion caused, and the occasional spectacular failures which occur when residual stress issues go unresolved. Residual stress relief is allowed for, and sometimes required, by most relevant national and international standards. However, this is almost universally in the form of PWHT, which remains by far the most accepted method. Other methods such as flame and induction heating are often used where PWHT is impractical [54], however all of the 'advanced' methods discussed here are still mainly at the experimental stage of development.

Prospect for future research

Arguably, the most successful fundamental studies into residual stress reduction mechanisms take a reductionist approach, using the simplest geometric cases so that the underlying processes can be more easily revealed. This is especially important when one considers that for even relatively simple cases the distribution of material properties, and the thermal and residual stress fields, may be quite complex. However in the practical application of these concepts, even more complex situations are common. For example, in multi-pass welds and additive-layer manufacture, further thermal cycling during the subsequent deposition of additional weld metal causes secondary metallurgical transformations, and affects the residual stress in previous layers [25, 79, 160]. Driven by the practical need for stress-reduction techniques in industry, it is likely that a great deal of prospective research will focus on applying stress-reduction methods to these more complex cases.

Several of the techniques mentioned above are relatively new, and therefore the limits of their application are not well mapped. For example, the limit of material ductility at which post-weld rolling may be successfully applied is not currently known, and the effects of rapid weld metal quenching during localised cooling (which, of course, vary greatly depending on the material used [116]) have not been fully explored. For these processes to be applied practically, there is a need for such limitations to be more fully understood.

Until relatively recently, experimental studies of welding residual stress and stress reduction methods have been confined to 'post-mortem' stress analysis, ie. determining the residual stress state after a process has finished. Consequently, modelling has been the main source of information on the evolution of strain during the process itself. However, as neutron and synchrotron diffraction instruments continue to develop, there has been increasing interest in the use of diffraction techniques to study welding residual stress formation *in situ*. So far, the focus has been on observing

the phase transformations which occur during weld metal cooling [157, 161, 162]. However, it is likely that in the near future, simultaneous *in situ* measurements of phase fraction and strain/stress will be important in understanding the interplay between microstructural evolution and residual stress.

Concluding remarks

Residual stress due to welding is an ongoing problem in engineering which affects multiple material and structural failure mechanisms. The current development of residual stress reduction technologies is driven by the high cost and inherent limitations of conventional processes such as post-weld heat treatment, and has been aided by continual advances in measurement methods and computer modelling capability. Since stress formation during welding is affected by thermal, mechanical and material factors, there has been a proliferation of different approaches to the problem based on these different physical mechanisms. Some techniques (notably the mechanical methods – rolling and global mechanical tensioning) have been proven capable of comprehensively changing the distribution of stress in a weld, but all come with their own practical limitations. Consequently, it is likely that a greater degree of specialisation will occur as these processes develop, since each is more suited to particular materials and applications.

Using the processes described above, some very encouraging results in terms of the residual stress distribution have been achieved in recent years. It is now necessary to consolidate such results with research into the accompanying material properties and microstructure, to show that these new stress reduction techniques can be safely applied to structural welds outside of the laboratory.

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